HUYGENS ATTITUDE RECONSTRUCTION BASED ON FLIGHT ENGINEERING PARAMETERS

M. Pérez-Ayúcar [1], A. Sarlette[1], P. Couzin[2], T. Blancquaert[1], O. Witasse [1], J.-P. Lebreton[1]

[1]*Planetary Missions Division, Research and Scientific Support Department, ESTEC-ESA, Noordwijk, The Netherlands.*
[2] *Satellites scientifiques et d'observation, Alcatel Alenia Space, Cannes, France*
Email: mperez@rssd.esa.int, asarlett@rssd.esa.int, Patrice.Couzin@alcatelaleniaspace.com, thierry.blancquaert@esa.int, owitasse@rssd.esa.int, jplebret@rssd.esa.int

ABSTRACT

Huygens is ESA's main contribution to the joint NASA/ESA/ASI Cassini/Huygens mission to Saturn and its largest moon Titan. The Probe, delivered to the interface altitude of 1270 km above the surface by NASA/JPL Cassini orbiter, entered the dense atmosphere of Titan on 14 January 2005 and landed on the surface after a descent under parachute of slightly less than 2.5 hours. Huygens continued to function after landing for more than 3 hours. Data was transmitted and successfully recovered by Cassini continuously during the parachute descent and for 72 minutes on the surface.

Although the Huygens attitude reconstruction based on the flight engineering parameters was not foreseen during the development phase (no gyros were included), a rough descent under parachute and indications of an anomaly in the probe spin direction make the engineering dataset valuable in the frame of the ADRS (Huygens Attitude Determination and Reconstruction Subgroup) as a complement to the scientific measurements. In addition, several scientific teams have a strong interest in understanding the orientation of the probe for interpreting their data, as DISR (Descent Imager and Spectral Radiometer) and HASI-PWA (Huygens Atmospheric Structure Instrument-Permeability, Wave and Altimetry).

In this paper we describe the engineering parameters used for the Probe attitude reconstruction (Clausen et al., 2002), namely the radio link AGC (Automatic Gain Control), RASU and CASU (Radial and Central Accelerometer Sensor Units) and RAU (Radar Altimeter Unit). We explain the methodology applied to indirectly infer the attitude information from the measurements of these sensors. We also discuss and present the reconstructed information related to attitude: spin rate and azimuthal position (during the atmospheric descent), and landing orientation. Tip and tilt implications are still being worked at the time of writing. Preliminary data on their behavior is presented.

1. INTRODUCTION

The Huygens Probe successfully dived into the dense atmosphere of Titan on 14 January 2005 and landed on the surface after a descent of slightly less than 2.5h (Lebreton et al., 2005).

In the context of the Huygens mission, the Cassini/Huygens Descent Trajectory Working Group (DTWG) aims at the reconstruction of the Probe entry and descent trajectory (Kazeminejad, 2005). The Attitude Determination and Reconstruction Subgroup (ADRS) is a subgroup of the DTWG that focuses on the reconstruction of the attitude profile during the descent and on the surface. The knowledge of the Probe orientation is required for the correct interpretation of the scientific data by the Science Teams.

The Huygens Probe included a set of engineering sensors for triggering the descent sequence, as explained in Clausen et al. (2002). Among these, some were especially sensitive to attitude disturbances, although they were not conceived for attitude reconstruction. A precise and straightforward attitude reconstruction would have been achieved if a set of gyroscopes had been included in the Probe system. Unfortunately it was not the case.

Early data analysis indicated that the Probe had a rougher than anticipated descent under parachute, and that an anomaly in the probe spin direction had occurred. Several instrument teams expressed their strong interest in understanding the orientation of the probe for interpreting their data, as DISR (Descent Imager and Spectral Radiometer) and HASI-PWA (Huygens Atmospheric Structure Instrument-Permeability, Wave and Altimetry). Therefore, the engineering datasets became of high value for attitude reconstruction as a support to the analysis and interpretation of the scientific measurements.

2. ENGINEERING PARAMETERS USED

The engineering parameters used as data inputs for the analysis presented in this paper are described in this section. Please refer to Clausen et al., (2002) for further details.

2.1. CASU – Central Accelerometer Sensor Unit

A set of three accelerometers monitored the Huygens entry for commanding the parachute deployment. This telemetry provides the deceleration in the x-axis (vertical axis of the Probe) with a sampling rate of 1 Hz and an accuracy of 40 mg. All 3 CASUs present similar in-flight data and behavior, so as an example CASU 1 data is shown in Fig. 1.

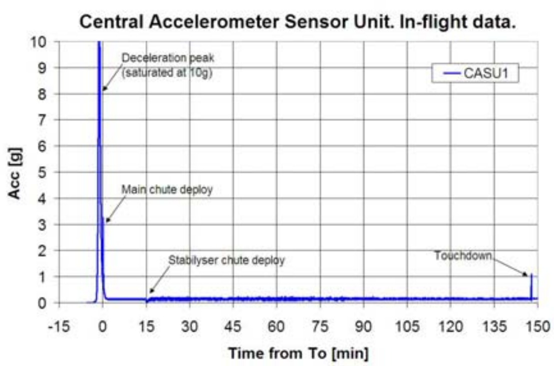

Fig. 1. Huygens in-flight data from the Central Accelerometer Sensor CASU 1. The main events of the mission are captured in the graph: main deceleration peak, main and stabilizer chutes deployment, and touchdown.

With a 1Hz sampling rate, the fast impact shock signature (~tens of milliseconds) was difficult to catch by CASU. Although there is indeed a spike observed in CASU, it does not capture the peak deceleration actually encountered (~15g).

2.2. RASU – Radial Accelerometer Sensor Unit

RASU is a set of two highly sensitive accelerometers that provides the radial acceleration. The raw values (shown in Fig. 2) are used by the on-board processor to compute a near real time spin rate estimation for distribution to the instruments in the DDB (Data Descent Broadcast). RASU is telemetered at 4 Hz with a 0.47 mg accuracy.

Due to the loss of chain A (Lebreton et al., 2005), only one of the raw RASU datasets is available on-ground. Nevertheless, an analysis of the processed DDB for both chains (available from the instruments internal telemetry), indicates that both sensors were measuring similar values and functioning nominally.

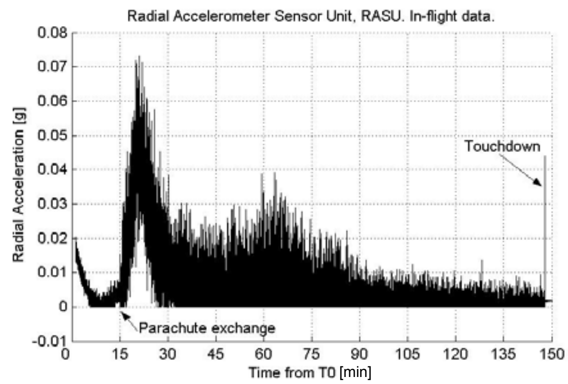

Fig. 2. Huygens in-flight raw data from the Radial Accelerometer Sensor RASU. Note the data is trimmed at zero. The touchdown shock is captured.

2.3. AGC – Automatic Gain Control

This telemetry parameter is the control word of the second coherent AGC loop in the digital part of the receiver. A detailed description of the receiver chain can be found in (Popken, 2004). Reported at 8Hz, it is proportional to the signal power received on board Cassini. The received chain B signal strength reconstruction (Pérez-Ayúcar et al., 2005) is shown in Fig. 3. The AGC has been flight-calibrated, being the conversion to signal-to-noise ratio E_s/N_0) based on the Probe Relay Test analysis.

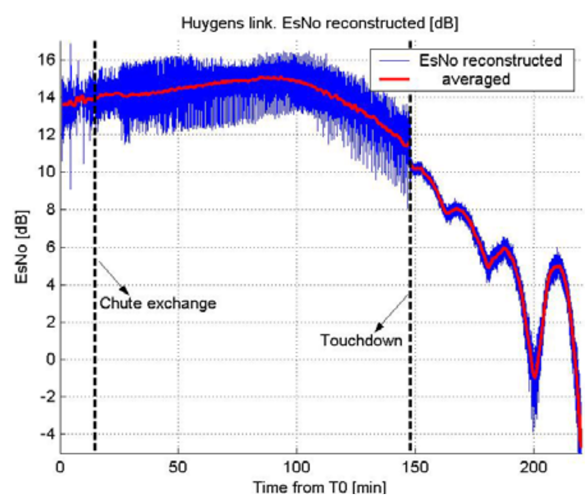

Fig. 3. Huygens in-flight data from the Automatic Gain Control AGC, converted into power to noise ratio, E_s/N_0.

The 3-4 dB band was expected (Pérez-Ayúcar, 2004): the non-symmetric PTA (Probe Transmitting Antenna) radiation pattern was scanned in every rotation while the probe spun down to the surface. Spin cycles are clearly distinguishable in the raw signal (see zoom in Fig. 6), playing a key role for attitude reconstruction and confirming a spin reversal anomaly. Probe touchdown is marked by the 'flat line' occurrence at 2h 27.8min after t_0 (time that the first parachute deploys), as spin stops. All relay link functions survived this event and continued working nominally after landing.

2.4. RAU – Radar Altimeter Unit

Huygens successfully monitored the altitude during the final descent with a pair of redundant Radar Altimeter Units working at 15.4 and 15.8 GHz (Lebreton and Matson, 2002).

The Huygens attitude motions in the lower part of the atmosphere can be derived from the analysis of the returned echo telemetries. Unfortunately, unfolding the attitude and the surface properties is subtle and, at the time of writing, the work is still on-going. So the RAU dataset is not included here.

3. THE RESULTS IN THE DESCENT PHASE

The accelerometers readings were analysed as the primary source of information for the descent attitude reconstruction. Unfortunately, the correlation between the RASU and CASU data did not provide the expected identification and quantization of the full attitude vector (Sarlette, 2005b). The sensitivity of CASU is rather coarse. Its operation range of ±10g (designed to monitor the entry deceleration peak and trigger the Huygens parachute sequence), comes at the expense of a poor resolution. The more subtle attitude perturbations are masked by the noise (see Fig. 5).

3.1. The 3 phases of the descent

Following a spectral analysis of RASU and CASU data (details and the spectra plots can be found in Sarlette, 2005a), the following three qualitative phases of the descent are inferred:

- Main chute (160 – 110 km altitude): relatively *calm* descent, no large attitude disturbances. A main frequency is found at ~0.8 Hz (Fig. 4).

- Stabilizer chute, initial phase (110 - ~30 km altitude): *rough* ride after its deployment, until 4000 sec in the mission. A main frequency is found at 1 Hz.

- Stabilizer chute, end phase (~30km - surface): the oscillations are *damped* in this phase, but still higher than during the main chute phase. A dichotomised frequency is present. Along with the 1 Hz stable component, a decreasing frequency from 1 to 0.6 Hz is recorded by the accelerometer.

These phases can also be seen qualitatively in the time domain, as illustrated in Fig. 5.

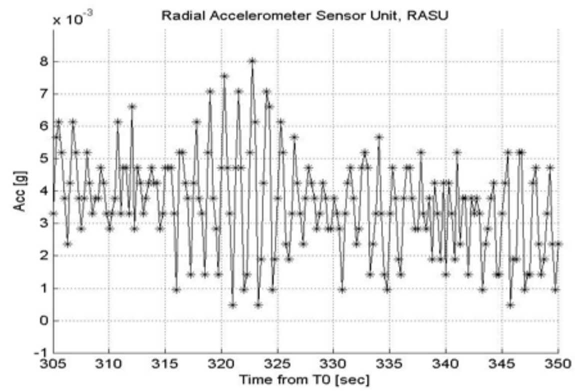

Fig. 4. RASU zoom-in. An oscillation of ~0.8 Hz is observed on top of the nominal centrifugal force (due to spin).

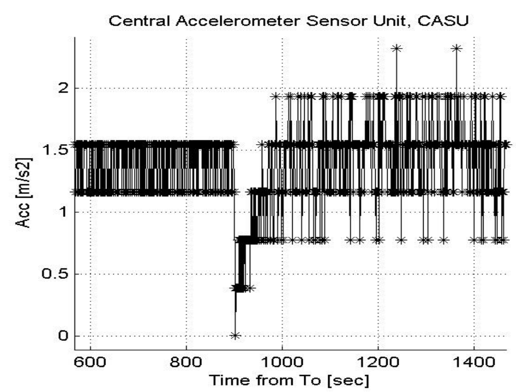

Fig. 5. CASU data at parachute exchange. A calm descent is observed under the main chute (variation of one LSB, due to quantization: g_{titan} is nominally 1.354m/s^2). A rougher descent occurs with the stabilizer chute (5 LSB change!).

A simplified model of coning and pendulum motions (using the previous oscillation frequencies) was performed in order to correlate the simulated behaviour and the flight measurements. The max-min acceleration values obtained by simulation were compared to the actual mission measurements for various values of the two parameters. The results (Sarlette, 2005b) show the following general behaviour:

- The probe seemed to oscillate around a 'fixed point' around 10 cm above the accelerometers position, so within the probe shell.

- The inclination envelope of the Probe horizontal plane is constrained to:

    - *0° to 4°* under main chute.

    - *4° to 9°* at the beginning of the stabilizer chute phase.

    - *1° to 5°* at the end of the stabilizer chute phase.

3.2. The spin sign: the reversal anomaly

As explained in detail in (Pérez-Ayúcar et al, 2005) the analysis of the radio link patterns confirmed an unexpected spin reversal in the mission: the AGC patterns before and after the inversion correlate well only if one is time-reversed. As a result, the Huygens in-flight spin direction has been estimated as *counter-clockwise CCW* (seen in the velocity direction) for the *early part of the descent* (consistent with the spin imparted at separation from Cassini), and *clockwise CW* for the whole stabilizer chute phase. This is non-compliant with the Probe specification.

3.3. The absolute azimuth reconstruction

The estimation of the azimuth can be performed by integrating the spin rate, in turn obtained from the radial acceleration (RASU). However, this method is not accurate enough as it relies on an integration and therefore it is subject to biases and to the assumption of an initial absolute reference. Another finer method, the AGC manual counting, remarkably provides absolute azimuth as a function of time, with respect to a known point in the sky, Cassini.

The Probe Transmitting Antennas (PTA) are not ideal but present an azimuthal asymmetry (Clausen et al., 2002). As Huygens spun down to the surface, the received power at Cassini showed periodic variations every rotation. The PTA gain pattern was measured before launch in a representative mock-up, so by comparison one can estimate the absolute Orbiter azimuth in a Probe body-fixed frame. It is assumed that the Probe is vertical and spins ideally, so that the elevation is considered fixed (at least for several spin periods) and equal to the PAA. The error associated to this assumption is assessed later in this section. The elevation slowly evolves with time, and is also taken into account.

After obtaining an absolute azimuth profile in the Probe fixed reference frame, a geometric conversion is applied to express it on a Titan's local frame.

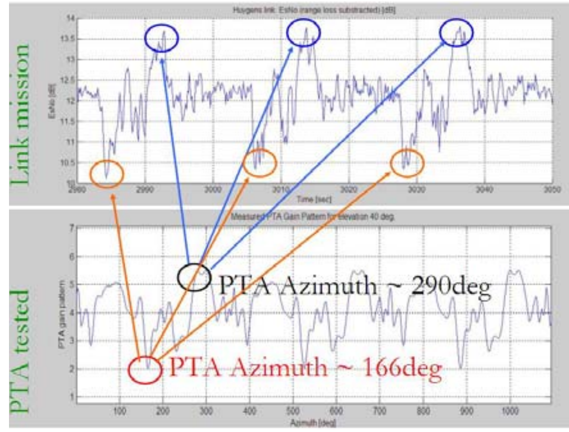

Fig. 6. The AGC manual counting method, used to derive the absolute azimuth (in Probe body fixed axis) by comparison of the AGC signal (upper graph) and the antenna measured patterns (bottom graph).

A summary of the derived Huygens azimuth versus time is presented in Fig. 7 in terms of complete rotations (modulo 360 of the un-wrapped azimuth). The Huygens Probe completed 24 rotations CCW followed by a spin reversal and 330 rotations CW, before landing on Titan's surface.

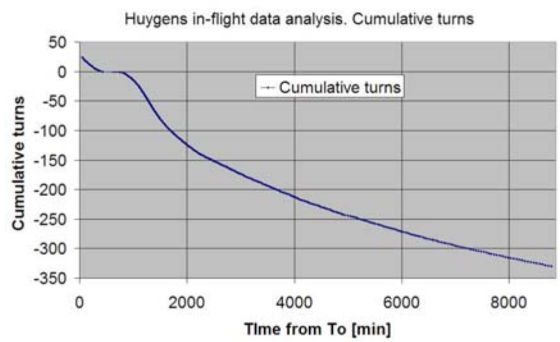

Fig. 7. Reconstructed cumulative turns during the Huygens descent, from link establishment until touchdown. The Huygens Probe completed 24 rotations in the CCW direction and 330 rotations in the CW direction.

The error on the Probe azimuth is based on the error inherent to the AGC analysis process, and the error in the conversion of reference frames. An extended explanation is found in (Sarlette et al., 2005b).

Regarding the inherent error in the identification of the peaks, the main contributors are: 1) the tested Antenna Gain Pattern data is limited to a 2° step (for both azimuth & elevation). This influences both the selection of the PAA and the matching of the peak in azimuth; 2) the AGC sampling rate (8Hz) implies that as the period of the signal decreases, fewer points are available and therefore the angular resolution decreases; 3) the pixel size when visually identifying the peaks on a screen. All those contributions are independent; hence a root-of-squares estimator has been computed. Although dependent on time, its value never exceeds ± 5 deg.

Regarding the error in the frame conversion, an attitude disturbance in tip - tilt induces an azimuth error when converting from the PTA (Huygens body fixed) reference frame to the Titan's local surface frame. A complex estimation was carried out in (Sarlette, 2005b), summarized in Fig. 8. In the plot, the local Titan's azimuth maximum error is presented, for several inclinations of the Probe horizontal plane.

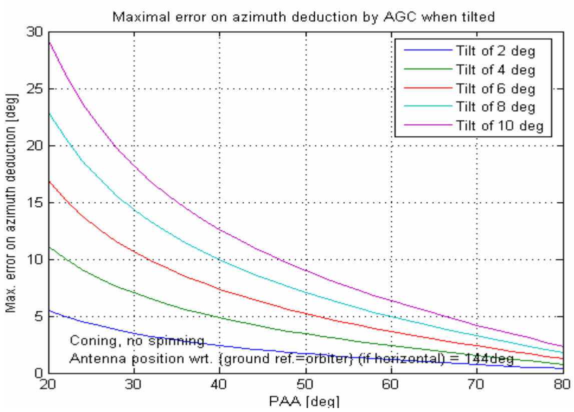

Fig. 8. Error estimates in Huygens azimuth (in Titan's local frame), implied by the assumption of a Probe vertical, for several actual inclinations of the Probe horizontal plane.

The error estimation is accordingly:

- Max values up to ~30deg @ start of mission
- Less than 3deg @ touchdown

3.4. The spin rate reconstruction

The most accurate way of obtaining the spin rate is by the derivative of the absolute azimuth obtained as described in section 3.3. Nevertheless, the azimuth values from the manual counting method are not optimum at:

- the spin peak, where the rotation (~10 rpm) is fast wrt the sampling rate of 8Hz. Fewer samples per period are hence available. In addition the rather strong attitude disturbances in this interval (rough early descent with the stabilizer parachute) are also reflected in the AGC.

- the spin reversal: as the Probe stopped spinning, the repetition pattern was not present, and the peak identification uncertain.

Spectrogram (AGC-FFT method) is a coarser but useful method to fill in these gaps. The spectrogram of the Huygens AGC signal is depicted in Fig. 9.

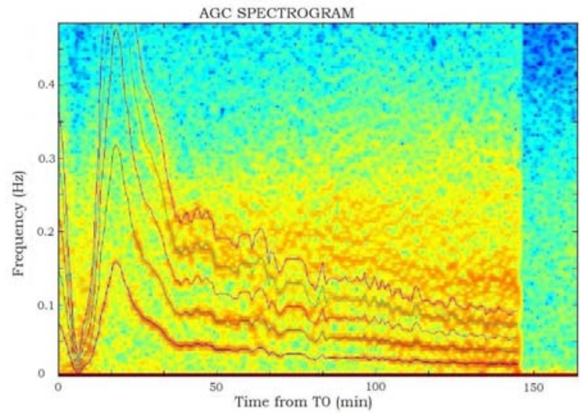

Fig. 9. The spectrogram of the AGC signal. The AGC-FFT method is used to derive a filtered spin rate (superposed lines) from the raw AGC signal. Some of its harmonics also appear in the FFT.

The dynamic FFT does not provide absolute azimuth, only a heavy-filtered spin rate, which in turn can be time-integrated to find azimuth values. Unfortunately, the frequency resolution achieved by an FFT analysis for an 8Hz signal is directly proportional to the duration of its periodic cycles. During a large part of the descent and close to the surface (where the main scientific interest for DISR and HASI-PWA resides) the rotation was slow (less than 3 rpm) and therefore the spin resolution is coarse. The method is only used around the spin peak (Fig. 11).

In the inversion, a more appropriate method relies on the occurrence of RASU values. RASU cannot be used directly to derive the spin rate since only positive values are transmitted in the telemetry (design feature). The high sensitivity of the sensor is such that attitude disturbances other than the centrifugal spin are clearly recorded (Fig. 10), as wobbling, pendulum motion, etc... Assuming that the disturbance implies an offset in the measured acceleration, equally distributed around its mean value, the smoothed median is a good indicator of the instantaneous radial acceleration. Again, the method does not provide absolute azimuth, only a filtered spin rate, which in turn can be time-integrated to obtain azimuth values. The error in this method is large for low spin rates. The spin rate is computed as a square root of the raw acceleration, so the fixed quantization step (~0.47mg) in the RASU telemetries implies a variable step when expressed in rpm, increasing as the spin rate decreases. Many of the near surface measurements are therefore in the level of the quantization step, and the retrieval of the spin rate is not as reliable as in the AGC method.

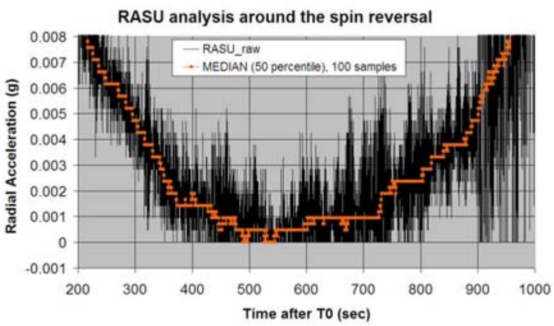

Fig. 10. The RASU median method. RASU data is cut at 0g. The raw data reflects noisy attitude disturbances around the centrifugal mean force (due to spin). The median value (non smoothed) is a good estimator of the centrifugal force.

Therefore, the consolidated spin rate of the Probe has been reconstructed based on these combined methods, as depicted in Fig. 11.

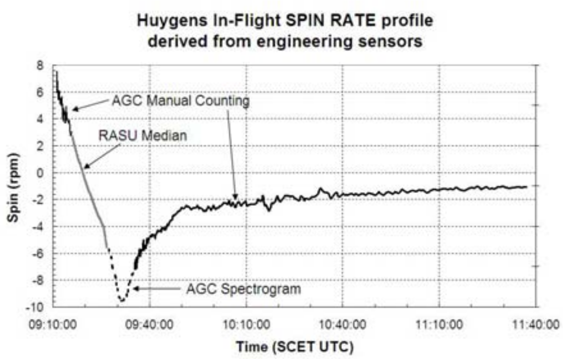

Fig. 11. Reconstructed spin profile: the RASU median method is used around the spin inversion, the AGC spectrogram in the peak, and the AGC manual counting otherwise.

4. THE RESULTS ON THE SURFACE PHASE

4.1. Impact and transient period

SSP dedicated sensors dated with best accuracy the touchdown event at 8870 sec (2^{h} 27.8^{min}) after t_0 (Lebreton et al, 2005). Still, in the link data a frequency glitch is observed at 8872 sec (Pérez-Ayúcar et al., 2005)), attributed to the impact shock. Since the telemetries from the link are time- stamped in the PSA onboard Cassini, while the Huygens data are stamped on the Probe computers, the difference could be simply explained by a datation accuracy issue (under investigation).

The touchdown event is marked, in the accelerometer readings, by a shock and a transitory oscillation until the measurements freeze. The transitory or bouncing phase is several seconds long, as illustrated in Fig. 12. In the RF power domain, the AGC froze at 8873.5 sec after t_0.

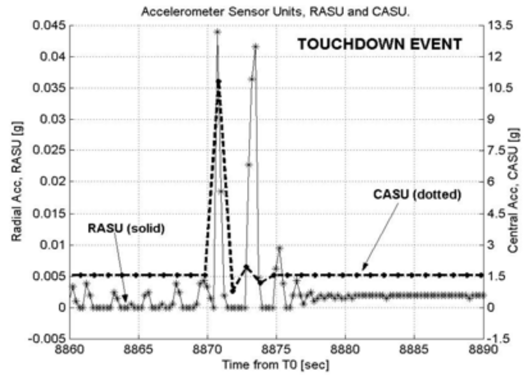

Fig. 12. Touchdown signature in CASU (dotted) and RASU (solid). Please note the different scales. After the peak shock, a 7-8 seconds transient is observed.

4.2. Tip-tilt implications

No clear conclusions can be made of the tip-tilt and the impact dynamics from the AGC and accelerometers data. CASU's resolution is coarse, so the component of Titan's gravity (g*cos(inclination)) vary a lot from one to the next quantization step. RASU is very sensitive, and could constrain the values attained by other teams, but being a one direction measurement by itself, it does not provide a unique solution. Anyway, since RASU is measuring a positive value, it means that the Probe is inclined with the RASU in the lower semi-plane. The angle β between the RASU radial position in the Probe and the direction of maximum inclination (shown in Fig. 13) can be obtained as in equation (1).

$$\beta = a\cos\left(\frac{RASU\_acc}{g \cdot \sin(inclination)}\right) \qquad (1)$$

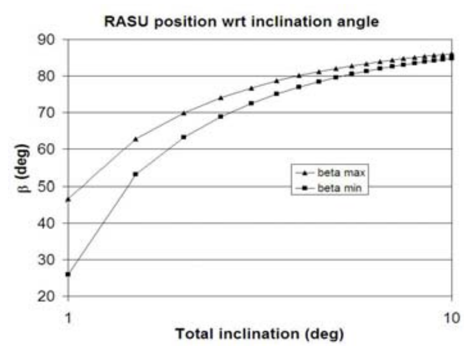

Fig. 13. Constrains in the Huygens β angle (angle between the RASU radial position in the Probe and the maximum inclination direction) on the surface. X axis is logarithmic. The 2 curves delimits the resolution errors (in the quantization of the raw values and g_{titan}).

4.3. Azimuth estimation

The AGC signal has been extrapolated to obtain a simple envelope of values of Huygens' absolute azimuth in Titan's reference frame, assuming that the movement after touchdown either stopped at 8870 sec or continued with the same spin rate until the AGC signal froze, at 8873.5 sec. This simple assumption does not include any bouncing or retro-movement after impact.

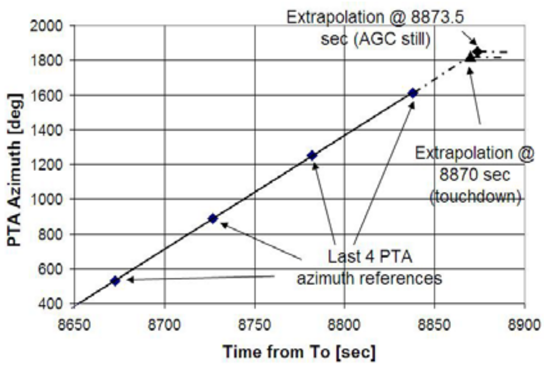

Fig. 14. Azimuth estimation after landing, based on the AGC data. The 4 last AGC-derived azimuths are extrapolated at 8870sec time (official touchdown event) and 8873.5sec (AGC freezes). The 0 azimuth corresponds to an arbitrary integer number of 360 deg.

The azimuth of the Y-axis is estimated to be confined between the 150˚ and 125˚ wrt the East direction. Therefore the DISR cameras, situated in the +Z-axis, should be looking S-SW, as depicted in Fig. 15. Reconciliation with other team's findings is on-going.

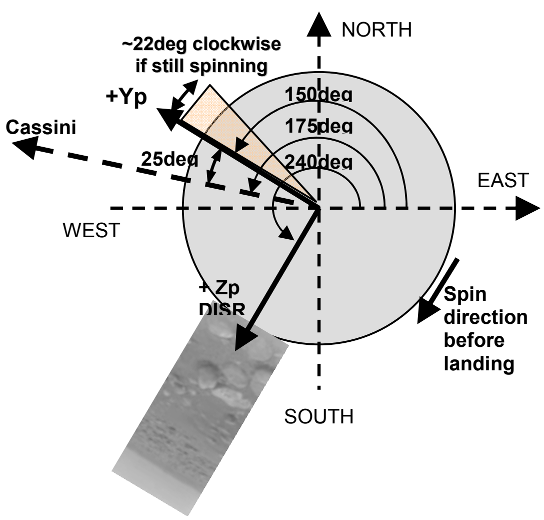

Fig. 15. Estimated landing orientation from the AGC data. According to the analysis, the DISR cameras should be looking in the S-SW direction.

4.4. Stability of the probe on the surface

Regarding the long term stability after landing, a sinking or movement can be surely ruled out looking at the accelerometer profiles: CASU 2 and 3, and RASU are stable, as shown in Fig. 16. CASU 1, though, presents a drift, but it is most likely to be caused by temperature effects.

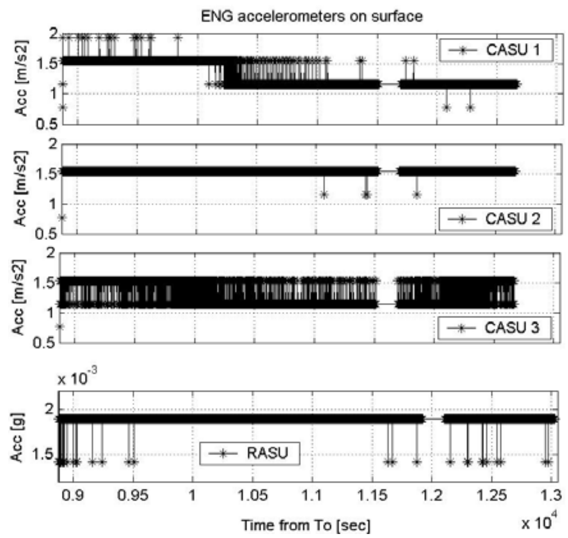

Fig. 16. Surface phase as measured by the Huygens central and radial accelerometers (CASU and RASU).

5. CONCLUSIONS

The characterization of some aspects of the Huygens attitude during its descent and landing has been achieved, based on the Probe engineering sensors data, despite the fact that they were not designed for post-flight attitude determination. The results are being used by the Huygens science teams to better interpret their data.

For the descent phase, an accurate absolute azimuth (and error) model has been created, with the confirmation of a spin reversal and a non-compliance of the spin rotation sense of the Probe. This information is crucial for the analysis of the cameras data. A coarse estimation of the amplitude of the oscillations seen under the parachutes has been made: calm descent under main chute (0-4˚), a rough early descent with the stabilizer (4-9˚) and a moderately calm late descent with the stabilizer chute (1-5˚). The frequencies of these oscillations have been studied and seem to be connected to the probe-parachute system dynamics.

For the surface phase, the attitude characterization was attempted, with the conclusion that the cameras are probably showing a S-SW view of Titan's landscape. A transitory phase lasting several seconds is captured after impact. The total inclination at the surface is constrained by the engineering sensors measurements, but no appreciable after-landing-movement is inferred.

As a lesson learnt, the Probe attitude knowledge, essential for the scientific data interpretation, could have been unambiguously reconstructed with the inclusion of dedicated attitude measurement devices as gyroscopes in the system design. Not being the case, a careful optimization of the existing onboard engineering sensors, as well as a data analysis plan, would have largely improved the understanding on this issue.

For future entry probe missions it would be desirable to apply all this experience gained in such a successful mission, Huygens, at the early stages of the mission design.

6. REFERENCES

Clausen K. C., Hassan H., Verdant M., Couzin P., Huttin G., Brisson M., Sollazzo C., Lebreton J.-P., , *The Huygens Probe System Design*. Space Science Reviews 104: 155-189, 2002.

Kazeminejad B., Atkinson D. H., Pérez-Ayúcar M, Lebreton J-P, *First Application of the Huygens Descent Trajectory Working Group Trajectory Reconstruction Algorithm to Huygens Data*, Proceedings of the 3rd International Planetary Probe Workshop IPPW3, Anavyssos, Greece, 2005 (this issue).

Lebreton J.-P., Witasse O., Sollazzo C., Blancquaert T., Couzin P., Schipper A-M., Jones J., Matson D., Gurvits L., Atkinson D., Kazeminejad B., Pérez-Ayúcar M.. *Huygens Descent and Landing on Titan: Mission Overview and Science highlights*, Nature, submitted, 2005.

Lebreton J.-P., Matson D. L., *The Huygens Probe: Science, Payload and Mission Overview.* Space Science Reviews 104: 59-100, 2002.

Pérez-Ayúcar M., Couzin P., Lebreton J.-P., Witasse O., *Huygens Radio Link In-Flight Performance*. Proceedings of the 3rd International Planetary Probe Workshop, Anavyssos, Greece, 2005.

Pérez-Ayúcar M., *Huygens Data Link Performance Analysis*. HUY-AN-77, ESTEC / ESA Technical Note, 22 Oct 2004.

Popken L., *Model of Receiver Design Flaw – Crucial for Huygens Space Mission Recovery*. IEEEAC paper#1262, Vers. 3, 0-7803-8155-6/04, 2004.

Sarlette A., Pérez-Ayúcar M., Witasse O., Lebreton J.-P., *Comparison of the Huygens mission and the SM2 test flight for Huygens attitude reconstruction*. Proceedings of the 3rd International Planetary Probe Workshop, Anavyssos, Greece, 2005a.

Sarlette A. *Characterization of the spin and attitude of the ESA Huygens Probe during its descent onto Titan using the engineering dataset.* Graduation Thesis, Liege University, 2005b.